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A Final Report on

A Study of the Surface Layers at an Air-Water Interface

by

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This is the final technical report on a study of the surface layers at an air-water interface. In the work covering the period from 1 January 1984 through 31 December 1989, there were five phases, viz., completion of studies in the air above the interface, numerical simulation of the surface layers, development of instrumentation, studies of the water layer, and the development of flow visualization techniques and wave-generation models. All of the experiments were conducted in the Stanford Wind, Water-Wave Research Facility, which has a 20 meter long test section and can produce windspeeds to about 14 m/s.

Studies in the air flow focused on the structure of the pressure and velocity fields, their impact on the transfer of momentum and energy to the water waves, the characteristics of the water waves, and the effect of the waves on turbulence production and the related bursting phenomena. The numerical simulation addressed the heat, mass and momentum exchange at a phase-changing, gas-liquid interface. Two-dimensional, laminar flow was simulated by the Keller Box

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19. Abstract (con't)

finate difference method.

Two significant instruments were developed during the course of the work to support the experimental program of measurements in the water layer. They were a wave-following laser-Doppler anemometer and an elementary planetary gear device for measuring the phase shift between the two components of the laser-Doppler anemometer. Measurements in the water were made in both fixed references and wave-following references frames. The results were reconciled by coordinate tranformation of the data. The character of the flow beneath wind waves was found to match that near a solid wall boundary layer. Wave turbulence interactions were defined by use of a nonlinear theory to predict the wave motions and separate them from the turbulent fluctations. Finally a new thrust on Langmuir cells was begun by use of a three-component laser-Doppler anemometer and fluorescence-based flow visualization.

Work currently in progress includes:

(1) numerical simulation of wave growth under wind action to reconcile the measured and theoretically-predicted growth rates.

(2) development of a film/video/image processing technique for detailed and quantitative flow visualization study of the dynamics in the water beneath the interface.

Table of Contents

1. Introduction

This final technical report for Contract N00014-84-K-0242, entitled "A Study of the Surface Layers at an Air-Water Interface", covers the period from 1 January 1984 through 31 December 1989. In that period the work included five phases, viz., completion of studies in the air above the interface, numerical simulation of the surface layers, development of instrumentation, studies of the water layer, and the development of flow visualization techniques and wave-generation models. This last phase of the work is still in progress under a follow-on grant from the ONR Fluid Mechanics Division. This summary is organized around these phases.

Appendixes 1 through 3 list, respectively, technical reports, dissertations, and publications supported by the Contract. In the text of this summary reference is made to the citations in these appendixes.

2. Up in the air

Under this contract, R. L. Street worked with Y. A. Papadimitrakis in bringing three papers to completion and publication, viz., Papadimitrakis, et al. [1986, 1987, 1988]. All of the work was based on experiments carried out in the Stanford Wind, Water-Wave Research Facility [SWWWRF], which has a width of about 1 meter, a water depth of about 1 meter and an air channel above the water of about 1 meter in height. The test section is about 20 meters long and the facility is equipped with an air inlet, exhaust fan, water-wave generator and a wave-damping beach. Wind speeds to about 14 m/s are feasible.

In Papadimitrakis, et al. [1986] the structure of the pressure and velocity fields in the air above mechanically generated water waves was investigated in order to evaluate their contribution to the transfer of momentum and energy from wind to waves. The measurements were taken in a transformed Eulerian wave-following frame of reference at wind speeds from 1.4 to 4.0 m/s and over wave of 25.4 mm amplitude and 1 Hz frequency. In this case the measuring volumes of the instrumentation follow a path that matches that for an irrotational channel flow over the mechanical waves, with the probes being at essentially a constant distance from the interface when they are very near to it. Specially designed high-sensitivity piezocrystal pressure transducers and two X hot film anemometers were used. The momentum and energy transfer rates supported by the waves were found to be dominated by the wave-induced pressure. The direct contribution of the wave-induced Reynolds stresses to the transfer processes was negligible.

Papadimitrakis, et al. [1987] focused on the characteristics of the water waves used in the previous paper. The amplitude and phase of the various wave components were deduced and the following conclusions reached: (1) the amplitude of the forced and free travelling second harmonics compares favorably with existing theories and (2) the nonlinearities of the primary wave, the interaction between short gravity waves and the primary wave, and the advection effects of wind drift are mainly responsible for the deviation of the measured phase speeds from the linear theory.

In Papadimitrakis, et al. [1988] the structure of the pressure and velocity field in the air above the progressive waves defined above was investigated in order to evaluate the influence of a mobile and deformable boundary on turbulence production and the related bursting phenomena. The Reynolds stress fluctuations were measured in the same transformed Eulerian wave-following frame of reference which was defined above. The structure of the wave-coherent velocity field was found to be very sensitive to the height of the critical layer below which the waves travel faster than the wind. In particular, when the critical height is large, the structure is also strongly affected by the Stokes layer (in the air), which under the influence of turbulence can have thickness comparable with the wave amplitude. The dependence of the structural behavior of the wave-coherent velocity field upon these layers results in considerable modifications of the turbulence-generating mechanism during the bursting cycle as the dimensionless wave speed [the ratio of wave speed to free stream wind speed] changes.

3. Inside the computer

The air-water interface is a classic and important case among those in which there is a phase-changing, gas-liquid interface. Klotz and Street [1985] examined the general case, as well as correcting and extending previous work by Kotake on the self-similar case. The two-dimensional, laminar boundary-layer equations of heat, mass and momentum at a smooth, phase-changing, gas-liquid interface were solved numerically by the Keller Box finite-difference method. The gas and liquid regimes were embedded in a single marching scheme which computes interfacial parameters implicitly. Results of both self-similar and non-similar boundary-layer computations were presented and effects of mild pressure gradient, a mean current in the liquid, and free-stream vapor concentration on the interfacial parameters were analyzed.

In order to assess the accuracy of the method, several self-similar problems were solved by Runge-Kutta integration and the results were compared to those obtained by the finite-difference scheme. Agreement was excellent in all cases.

4. Instrumentation

Two significant instruments were developed during the course of the work, namely, a wave-following laser-Doppler anemometer [LDA] and an elementary planetary gear device for measuring the phase shift between the two components of an LDA.

The wave-following LDA was designed and qualified to measure the water velocity in two directions beneath wind-ruffled, mechanically generated, progressive water waves. As reported in Cheung [1985] and Cheung and Street [1984] results show that the system performs very well in measuring mean and RMS velocity profiles. The LDA was operated in a back-scatter mode and the outgoing and returning beams were steered by a moving mirror operated by an optical scanner driven by input from a capacitance wave-height gauge. The objective was to steer the LDA beams so that the measuring volume remained at a prescribed distance below the air-water interface.

In fluid mechanics, physical quantities such as shear stress depend not only on the magnitude of two velocity components, but also on the phase lag between them. Therefore, given a velocity measurement system, it is essential to determine whether the phase shift between two velocity components can be accurately measured. In the present research, the measurements reveal a large, unexpected and to date unexplained correlation between the u- and w-velocities of the mechanically-generated wave component. One key question was whether or not this correlation resulted from error in the LDA. To answer this question, we constructed a device, composed of a planetary gear system, which produced a velocity whose horizontal and vertical components differed in phase by exactly 90 degrees [Jiang, et al., 1987]. From this device we determined that the LDA was accurate within plus or minus 2 degrees in determining the phase difference of the signals; an error far less than that needed to produce the spurious correlation.

5. Down in the water

The major work on the flow beneath the interface was carried out and analyzed by Cheung [1985] and Jiang [1990]. In their work the velocity fields beneath the air-water interface were determined in the SWWWRF for cases of wind-generated wave, with wind speeds ranging from 1.5 to 13.1 m/s, and of wind-ruffled mechanically generated waves of about 22 mm amplitude and 1 Hz frequency, with wind speeds ranging from 1.7 to 6.2 m/s. In both cases the velocity was measured in a fixed frame of reference with a two-component, LDA operating in forward-scatter mode. In the case of the mechanical waves, measurements were also made in an Eulerian wave-following frame of reference with the LDA operating in the backward-scatter mode [see Section 4 above or Cheung, 1985, or Cheung and Street, 1984].

5.1 Fixed reference frame measurements

In Cheung and Street [1988] we reported on fixed frame measurements. It was possible to determine the lengthscales and to evaluate the behavior of the mean, wave-related and turbulent components of the flows. The waves do affect the mean flows, even though the profiles remain essentially logarithmic and the wave field conforms generally with the results of linear theory. In the wind-wave cases the turbulent quantities behave similarly to those in flows over flat plates. They have different trends in the mechanical-wave cases, suggesting a coupling between waves and turbulence. Finally, measured values of the mean wave-induced shear stress were negative, leading to an energy transfer from the waves to the mean flow.

Using the Cheung [1985] data, Jiang, et al. [1989 & 1990a] examined wave-turbulence interactions. Wave-turbulence interaction may contribute to momentum and energy transfer in the near surface region beneath water waves. However, the nature and extent of this mechanism have not been well understood. A wave-separation technique was developed to study quantitatively the transports due to wave-turbulence interaction. In this technique a nonlinear stream function representation of the wave motion is determined so as to satisfy the kinematic and dynamic boundary conditions at the water surface. Wave-induced velocities are deduced from the stream function and the decomposed wave-induced and turbulent flow fields are obtained. This wave separation technique was applied to the Cheung wind-wave data. Coherence spectra indicate high correlation between turbulence and wave-induced motions at some frequencies. Time-averaged correlations between wave and turbulent velocities increase with wind speed and decrease with increasing distance from the interface. Although there is no significant momentum transfer due to the wave-turbulence interaction, this mechanism results in significant energy transfer among the mean, wave-induced, and turbulent flow fields. Finally, we showed that filtering techniques [for removing wave effects from data; see Cheung, 1985], which lack the input of wave physics and only correlate measured characteristics with the water surface displacement, are unable to distinguish wave motions from turbulence correlated with them.

Next, Jiang, et al.[1990c] estimated the dissipation of turbulent kinetic energy beneath the wind-generated water waves. A method based on the assumption of a universal inertial subrange in the velocity spectrum is thought to give a lower bound on the total dissipation rate. The rates determined by this method characterize only the amount of energy cascading down the spectrum as a result of the shear flow current in the water and do not represent the total rate of dissipation. The dissipation values at low windspeeds agree well with those in smooth-wall boundary layers and approach the dissipation rates in a fully rough, solid-wall boundary layer as the free-stream velocity increases. Tests of the

Lumley-Terray frozen-turbulence hypothesis (a generalized hypothesis for the case where the convecting velocity has a periodic component) show that an approach employing the integral of the entire velocity spectrum and Taylor's hypothesis, although adequate for solid-wall boundary layers, fails to determine the dissipation in the present case since measured turbulent velocity spectra are contaminated by waves at higher frequencies. No evidence of white-cap dissipation is found in the low frequency part of the spectra. Indeed, it appears that the breaking mechanism produces turbulence mostly in the high frequency part of the spectrum, namely, at frequencies close to and above the frequency of the dominant wave. Our results indicate that at relatively high windspeeds about 7 % of the energy input from the air to the water is dissipated by the shear flow, while 45 % is dissipated by wave breaking and about 6 % is transferred away from the turbulence to the underlying shear current by wave-turbulence interaction at frequencies near that of the dominant wave.

Finally, Monismith [1989] reported on the beginning of a new research thrust, motivated by the complex flow beneath the interface. His paper presented the results of measurements in the SWWWRF using a three-component LDA in combination with fluorescence-based flow visualization. His measurements show strong, organized secondary flows that were interpreted to be Langmuir cells. [Langmuir cells are streamwise vortices that form in the surface layers of oceans, estuaries and lakes in the presence of waves and a wid-driven drift current; they are thought to play an important role in mixed-layer dynamics, mixed-layer biology, and air-sea gas exchanges.] In our facility these Langmuir cells appear to vary in strength, position and number over time, leading to substantial low-frequency flow variations. He argued that this flow variability is characteristic of similar flows observed in nature; the variability that he observed is in fact a manifestation of a real instability of natural Langmuir cells. This work has spawned a new research thrust by Monismith with support of the National Science Foundation.

5.2 Wave-following reference frame measurements

Both Cheung and Jiang looked at mechanical waves in a wave-following frame of reference also. A phase-averaging technique was used to define the component associated with the monochromatic, mechanically-generated waves and to separate that component from the fluctuating one which is associated with wind-generated ripples and turbulence. Cheung and Street [1988] presented basic results for the Eulerian velocity fields beneath the interface for the case of the wind-ruffled mechanically-generated waves. The results confirmed that the waves affect the mean flow while the profiles still remained logarithmic in the transformed coordinates. The wave following results appeared as extensions of the fixed-frame results to shallower depths.

Jiang, et al. [1990b] continued the examination of these cases. In particular, they showed conclusively that, because of the water surface undulation, the Eulerian measurements by a fixed probe can be misleading and need to be corrected, e.g., before interpretation of RMS and shear stress data presented as a function of wave phase. In addition it was shown by nonlinear theory and confirming experiment that an Eulerian fixed-frame velocity measurement of the field beneath a pure sinusoidal wave yields an apparent and spurious mean current in the direction opposite to the direction of wave propagation.

When either the fixed frame data or the wave following data are converted to the other reference frame they are seen to be consistent. By using the wave separation technique described above, togethei with phase averaging with respect to the 1 Hz mechanical wave, it is possible to decompose the flow into mean, wave, turbulent and modulated components. The modulated component is that streaming flow [with zero mean] which follows the water surface and varies with wave phase; it is not symmetric with respect to the wave and clearly reacts to the expansion and compression of the streamlines caused by the fluctuating water surface.

6. Visualization and generation - work in progress

Under this project work was begun on two new thrusts, viz., the reconciliation of the measured and theoretically-predicted growth rates of waves under the action of the wind and development of a quantitative technique for determining the velocity field beneath the water surface by flow visualization. This work is continuing under a follow-on grant from ONR.

A comparison of theory and experiment revealed that the growth of short gravity-capillary waves is well described by viscous linear stability theory and that there is good agreement between inviscid linear stability theory and the results of experimental and numerical studies of the flow over solid, but progressive, monochromatic waves. However, Miles' inviscid linear instability theory and modifications to it are inadequate to predict the growth rates of reasonably long, wind-generated gravity waves. Measured growth rates are generally 2 to 5 times larger than predicted rates. There are a number of factors to be examined, including the role of the coupled air and water mean flow with which the water waves interact and the fact that experiments are often presented in terms of single dimensionless parameter while analysis shows that at least 4 are required. The program of research will examine the coupled air-water problem via a numerical simulation model.

In parallel, we are completing development of a flow visualization and image processing technique which will allow us to study the near surface water flow in great detail. Of particular interest will be the time and space variations of the flow. With such data in hand, we expect to be able to describe the temporal and spatial evolution of the flow and compute the flow vorticity, etc. The technique that we are using employs a vertical laser light sheet, neutrally buoyant reflecting particles and a high-speed (120 frames per second) movie camera. Film sequences are re-recorded onto video tape at 30 frames per second and analyzed on an image processing device. That device and associated software and displays allow generation of velocity vector fields, etc., which can then be analyzed in detail.

7. Conclusions

At the conclusion of this effort, we can say that the characteristics of the flow in the air above the interface are well defined. The characteristics of the flow in the water are better known than before, but questions remain, particularly with regard to wave-turbulence interaction, to Langmuir cells, and to the role of wave breaking in the transport and generation of turbulence beneath the interface. Unfortunately, the mechanisms which generate waves by extracting energy from the wind remain elusive, explaining to date only qualitatively the actual magnitude of the transfers.

Appendix 1. Technical Reports

T.K. Cheung, "A study of the turbulent layer in the water at an air-water interface," Department of Civil Engineering Technical Report No. 287, Stanford University, January 1985, 275 pages.

J.-Y. Jiang, R.L. Street, and S.P. Klotz, "Wave-turbulence interaction beneath an air-water interface," Environmental Fluid Mechanics Laboratory Report EFML 89-1, Department of Civil Engineering, Stanford University, January 1989, 44 pages & 25 figures [not distributed; available by request only].

Appendix 2. Dissertations

[Available from University Microfilms, Ann Arbor, MI]

T.K. Cheung, "A study of the turbulent layer in the water at an air-water interface," Department of Civil Engineering Ph. D. Dissertation, Stanford University, January 1985, 275 pages.

J.-Y. Jiang, "Wave-turbulence interaction and modulated flows beneath water waves," Department of Civil Engineering Ph. D. Dissertation, Stanford University, April 1990, approx. 150 pages.

Appendix 3. Publications

T.K. Cheung and R.L. Street, "A wave-following laser-Doppler anemometer," LASER ANEMOMETRY IN FLUID MECHANICS, Ladoan-Instituto Superior Tecnico, Portugal, 1984, pp. 123-140.

T.K. Cheung and R.L. Street, "The turbulent layer in the water at an air-water interface," Journal of Fluid Mechanics, 194, 1988, pp. 133-151.

T.K. Cheung and R.L. Street, "Wave-following measurements in the water beneath an air-water interface," Journal of Geophysical Research, (Oceans), 93, C11, 1988, pp. 14,089-14,097.

J.Y. Jiang, A.K. Prasad, J.R. Koseff, T.K. Cheung, R.L. Street and S.P. Klotz, "Can reliable phase measurements be made by laser-Doppler anemometry?" 3rd Int'l Symp. on LDA , ASME, FED-Vol. 55, 1987, pp. 59-62.

J.-Y. Jiang, R.L. Street and S.P. Klotz, "Wave-turbulence interaction beneath an air-water interface," Seventh Symposium on Turbulent Shear Flows, 1989, pp. 18.1.1-5.

J.-Y. Jiang, R.L. Street and S.P. Klotz, "A study of wave-turbulence interaction by use of a nonlinear water-wave decomposition technique," Journal of Geophysical Research, (Oceans), in press 1990a.

J.-Y. Jiang, R.L. Street and S.P. Klotz, "Modulated flows beneath wind-ruffled, mechanically-generated water waves," Journal of Geophysical Research, (Oceans), in press 1990b.

J.-Y. Jiang, R.L. Street, S.G. Monismith, and S.P. Klotz, "Turbulent energy dissipation beneath wind-generated water waves," Abstract, EOS, 71, 2, 1990c, p. 72.

S.P. Klotz and R.L. Street, "On the numerical computation of laminar boundary layers at a phase-changing, gas-liquid interface," International Journal for Numerical Methods in Fluids, 5, 1985, pp. 957-980.

S.G. Monismith, "Low-frequency turbulence and secondary flows under wind waves: Langmuir cells?" Abstract, EOS, 70, 43, 1989, p. 1166.

Y.A. Papadimitrakis, E.Y. Hsu and R.L. Street, "The role of wave-induced pressure fluctuations in the transfer processes across an air-water interface," J. Fluid Mech., 107, 1986, pp. 113-137.

Y.A. Papadimitrakis, E.Y. Hsu and R. L. Street, "Characteristics of mechanically-generated waves," J. of Waterway, Port, Coastal and Ocean Engineering, ASCE, 113(1), January 1987, pp. 39-59.

Y.A. Papadimitrakis, R.L. Street, and E.Y. Hsu, "The bursting sequence in the turbulent boundary layer over progressive, mechanically generated water waves," Journal of Fluid Mechanics, 193, 1988, pp. 303-345.